POWER HARVESTING WIRELESS SENSOR SYSTEM

A Design Project Report
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by
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Abstract

Master of Electrical Engineering Program

Cornell University

Design Project Report

Project Title: Power Harvesting Wireless Sensor System

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Abstract:

The goal of this project is to develop a self-powered wireless sensor system to measure the dynamics of helicopter blades. The hardware portion of this project is comprised of two major components. The first component involves the investigation of power harvesting techniques in order to power the sensor system using an oscillating piezoelectric element attached to the leading edge of the helicopter blade. The second component of the project is the design and layout of a circuit board that will interface a TI MSP430 microcontroller with a wireless transceiver as well as the desired sensors. As an intermediate step, a breakout board will be designed to interface the sensors to a MSP430 development kit. The final product will be a self contained circuit board that contains the selected power harvesting circuit and the microcontroller hardware. The microcontroller will execute software developed separately to transmit sensor readings at the fastest interval permitted by the power harvester. This unit will be attached to both experimental and production helicopter blades and improve the ease in acquiring and analyzing data about the blade dynamics for a variety of purposes.

Report Approved by

Project Advisor: Date:

Executive Summary

This project involved the design, fabrication, and assembly of hardware for a fully wireless sensor system to be installed on helicopter blades for characterizing blade dynamics. In coordination with the Laboratory for Intelligent Machine Systems at Cornell University, the project also involved the investigation of power harvesting for electronic devices using piezoelectric materials. Although power output from the piezoelectric actuators was insufficient for inclusion in the final design, piezoelectric materials remain a promising area of future research for power harvesting techniques. The system was designed to be easily extendable to incorporate future power harvesting work with minimal engineering effort.

The current system consists of Sensor/RF board powered by a TI MSP430 microcontroller using a TI CC2500 RF transceiver for wireless communications. Acceleration data for the characterization of blade dynamics is provided by a Bosch BMA150/BMA020 accelerometer that interfaces with the microcontroller. This data is transmitted to a nearby base station for data analysis. The system is receives power from a daughterboard that is mounted on top of the Sensor/RF board. The daughterboard is responsible for the extendability of the power source.

The system operates on firmware developed by Joshua Sirkin as an independent Masters of Engineering project in the Department of Mechanical and Aerospace Engineering. The software was developed on a TI eZ430-RF2500 development board in conjunction with a BMA150 development board. The Sensor/RF board was designed to execute firmware from the test platform with only minor modifications.

The system has been tested and can successfully interface with the accelerometer and output the data over the UART interface. However, the RF interface currently fails to link to the RF base station. Debugging this issue will require extra investigation.

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1 Introduction

The need for this project arose from helicopter development at Sikorsky Aircraft Corporation. Helicopters experience periodic and non-periodic vibratory loads during flight. Vibrations occur in the vertical, lateral, and torsional axes with fundamental frequencies as well as higher order harmonics. During development of new rotor designs, engineers need to be able to characterize the dynamics and measure the magnitudes of the harmonics. Specifically, engineers seek to minimize the magnitudes of certain harmonics that are undesirable. By placing a sensor system on the rotor blades, engineers can more effectively characterize dynamics and control vibration.

1.1 Current Solution

Sikorsky already has the capability to mount sensors on the rotor blades to characterize their dynamics. However, the current sensor units require wire connections from the cockpit for both power and communication. Due to the rotating hub, the wire connections must pass through a slip ring connected at the hub before entering the cockpit. Slip rings have two main drawbacks. First, the connections through a slip ring can be intermittent and temperamental to maintain. Second, installation of the slip ring requires significant time that could be better spent on other efforts.

1.2 Wireless Solution

A fully wireless sensor unit would solve the drawbacks presented by the current slip ring system. To become fully wireless, two separate aspects of the design must be modified–the power subsystem and the data transmission subsystem. Both components should provide similar performance to the slip ring system while adding considerable convenience.

2 Helicopter Blade Dynamics

A presentation by Austin Fang outlined the fundamentals of helicopter blade dynamics for the purpose of this project [1]. The rotor hub contains a flapping hinge to compensate for the discrepancy in lift forces on the blades as they rotate. Figure 1 shows the free body diagram of the forces that act independently on each blade.

A common mechanism for connecting blades to the rotor is shown in Figure 2 [1]. The flapping behavior is responsible for the vertical oscillations that this project seeks to characterize.

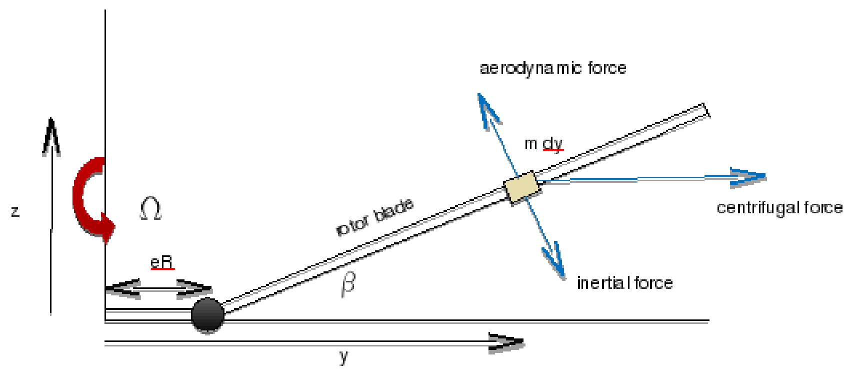

Figure 1: Blade forces free body diagram (Fang)

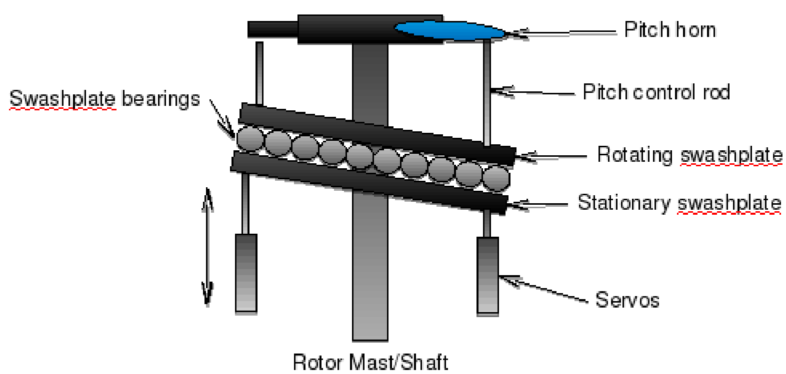

Figure 2: Rotor Blade Pitch Control (Fang)

Typically, the rotor rotates with a frequency of 4-5Hz (typically 4.3Hz) which also represents the fundamental harmonic for the flapping motion. The first 4 harmonics are the largest and most important for design analysis. In certain aggressive maneuvers, the blades may experience forces in excess of $10g$. However, these manuevers are outside the scope of the usage case for this design. The main concern is vibrations experienced during steady level flight, which will be less than $10g$.

3 Design Considerations

The helicopter environment and flapping characteristics drive the design considerations for this project. Physically, the hardware must be small enough to easily be mounted on or inside a helicopter blade. While a firm size requirement was not set, the TI EZ430-2500RF was used as a rough target size of 0.8” x 1.18”.

Next, the sampling rate of the accelerometer must be high enough to capture all relevant harmonics. The 4th harmonic has a frequency of approximately 16-20Hz. By the Nyquist Theorem, the accelerometer must have a sampling rate greather than 40Hz. Some level of oversampling should be incorporated as well. The accelerometer must also have a sufficent range to measure the forces experienced by the blade. Since the unit will only be used for steady level flight and will not be mounted at the tip of the blade, $8g$ was determined to be a suitable range.

Any wireless system in relative motion is subject to the Doppler effect. In this case, the transmitter will be rotating with the blade and the receiver will be located in a stationary location, likely the cockpit. The Doppler shift is affected by the radial velocity of the transmitter/receiver pair. Thus, a receiver located on the hub would not experience any frequency shift, but a receiver in the cockpit would. Equation 1 summarizes this relation.

$$f_D = \frac{v_{rad}}{\lambda} = \frac{\vec{v} \cdot \hat{r}}{\lambda} = \frac{f_c \vec{v} \cdot \hat{r}}{c} \tag{1}$$

For approximations, the linear velocity of the sensor unit can be used as a loose upper bound for the radial velocity. With the sensor 3.0m from the hub, the linear velocity is approximately 80m/s. Solving Equation 1 with this radial velocity and a carrier frequency of 2.4Ghz yields a Doppler shift of 640Hz. The frequency tracking loop of the RF transceiver must have a bandwidth greater than the expected Doppler shift.

Finally, minimizing power consumption is a key design goal, both in terms of hardware selection and software implementation. The sensor unit will be driven by a power harvester or by a battery, each having limited power. Minimizing power consumption will maximize the combination of duty cycle and lifetime.

3.1 Possible Solutions

From the beginning, the TI EZ430-2500RF development board was presented as the proposed development platform. The development board was a well integrated solution of a TI MSP430 microcontroller and a TI CC2500 RF transceiver chip. The combined platform also worked out of the box with a robust, open-source protocol stack developed by TI that was well suited for the application. Both chips are also known for low power operation. However, other combinations of microcontrollers and RF transceivers would have met specifications. Table 1 shows an estimated power budget for this application using a TI EZ430-2500RF [1].

The Bosch BMA150 accelerometer also came recommended from a former member of the Laboratory for Intelligent Machine Systems who had used it in a similar application. Accelerometers with similar specifications are also available from other manufacturers.

Component	Mode	Power (μW)	Duty Cycle	Weighted Power (μW)
MSP430	Active	440	6.0%	26.4
MSP430	Sleep	2.7	94%	2.54
CC2500	Transmit	63,600	6.0%	3820
CC2500	Receive	56,400	6.0%	3380
CC2500	Sleep	2.7	88%	2.38
Accelerometer	Active	600	6.0%	36.0
Accelerometer	Sleep	3	94%	2.82
Average Power Consumption				**7270**

Table 1: Estimated Power Budget for EZ430-2500RF System(Fang)

Power harvesting can be accomplished in many ways. The Laboratory for Intelligent Machine Systems was particularly interested in piezoelectrics for this and other applications. Solar power is another possible power harvesting technique.

4 Hardware Design

After using the ez430 development board, it was selected as the basis for hardware design. The BMA150 was selected as the accelerometer after examining alternatives and seeing no significant advantages over the BMA150. Piezoelectric power harvesting was chosen for the primary investigation due to group interest and size constraints that made solar panels unappealing.

The hardware design separates the functional components into a Sensor/RF board and the power system on a daughterboard. The daughterboard architecture allows flexibility in the power system without modifying or remanufacturing the more complex elements of the design. It also eases use in a lab environment where power supplies are available and reprogramming the microcontroller is necessary.

All board design was completed using the free license of the Eagle CAD suite. It is capable of generating industry standard Gerber design files which prevented lock-in with any particular PCB manufacturer. The interface was preferable to open-source tools with similar functionality.

4.1 Power Harvesting

As mentioned, piezoelectrics were chosen for the primary power harvesting investigation. The harvester used an off the shelf MIDE QuickPack piezoelectric actuator, shown in Figure 3. The piezeoelectric was connected to a beam with an airfoil that would be

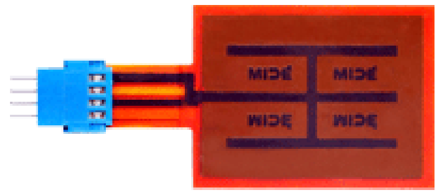

Figure 3: MIDE QuickPack Piezoelectric Actuator

mounted on the leading edge of the helicopter blade. The airfoil would cause the beam to oscillate in oncoming airflow, generating electric power in the piezoelectric actuator.

The electric output of a piezoelectric actuator can be modeled as a sinusoidal current source with a parallel capacitance [8] or as a sinusoidal voltage source with a series impedence [2]. The circuits are Norton/Thevenin equivalents. In both cases, the amplitude of the sinusoid is determined by the electromechanical dynamics of the piezoelectric actuator [9]. In general, the amplitude will increase as the strain in the piezoelectrical material increases.

The varying amplitude AC output of the piezoelectric actuator mandates a conditioning circuit before it can be used to power devices. Simply, the output requires rectification and filtering then regulation at a voltage level appropriate for the circuit [8].

Schottky Diode full wave rectifiers were chosen for power rectification. Schottky Diodes are superior to pn-diodes in low voltage applications because they have a forward voltage drop of 0.2V instead of 0.6-0.7V. In low voltage applications, this difference can represent a high percentage power loss. The initial discrete schottkey diode ICs were replaced with integrated full wave rectifier ICs built with Schottkey diodes. These ICs reduced wiring, space, and cost.

The next most important design choice for the conditioning circuit is the voltage regulator. A poorly chosen regulator can also result in large power losses. A switching regulator provides much higher efficiency. However, the voltage input to the regulator for this application was unknown. Proper regulator selection is difficult unless the circuit is definitively step-up or step-down. For preliminary testing, the Analog Devices ADP1111 regulator was selected. The ADP1111 is configurable for both step-up and step-down operation, as well as preset voltage output at 3.3V, 5V, and 12V.

As discussed in Section 6.1, experimental data indicated that powering the system using the MIDE QuickPack was not currently feasible. At this point, design efforts for power harvesting circuitry ceased to focus on designing the sensing and RF elements of the project.

4.2 Sensor/RF Board

As mentioned, the TI EZ430-2500RF was used as a basis for the hardware design of the Sensor/RF Board. The CC2500 reference design was consulted as well. The Sensor/RF board contains the microcontroller, accelerometer, RF transceiver, antenna, and supporting components. Power is supplied externally through the daughterboard interface. The board is designed to be powered from a 3V source.

Microcontroller and RF

The Sensor/RF board uses a TI MSP430F2274 microcontroller to interface with the other components. This is the same microcontroller used in the TI EZ430-2500RF board. It is configured to run off an internal oscillator at 1MHz. Using the interal oscillator reduces board size and power consumption of an external oscillator. The low clock rate also reduces power consumption and is adequate for the performance requirements of this application.

The Sensor/RF board uses a TI CC2500 RF transceiver chip for wireless transmission. The CC2500 is a fully integrated RF solution that goes all the way from raw data packets to modulated RF of various configurations. The microcontroller configures the CC2500 over a 4-wire SPI interface using the MSP430's UCB0 hardware module. SPI is an industry standard full duplex serial bus [10].

The CC2500 transmits with a 2.4GHz carrier. It requires a 26MHz external crystal to generate the necessary IF and RF frequencies. The crystal recommended by the CC2500 reference design would have increased the size of the board, so a 3.2mm x 5.0mm SMT crystal was used instead. The EZ430-2500RF uses the same type of crystal. The crystal has $C_L = 10pF$. According to the CC2500 data sheet, 15pF capacitors should be used with crystals of that load capacitance. The design uses the recommended 15pF capacitors, even though the EZ430-2500RF uses 27pF capacitors with the same crystal.

The CC2500 has a differential bidirectional RF interface. For optimal RF performance, the differential impedence seen by the port should be:

$$Z_{out} = 80 + j74\Omega$$

Connecting the RF interface to an antenna requires a combination balun and impedence matching network of passive components. The reference design emphasizes the use of 402 components for this network when specified. The surface mount antenna is unbalanced and has an impedence of 50Ω. The antenna is the same one used in the EZ430-2500RF, and the matching network is based on the one used by the development board as well.

Accelerometer Interface

The Bosch BMA150 accelerometer was chosen based on a recommendation and its attractive specifications. The BMA150 is a small package (3mm x 3mm) accelerometer with 3-axis measurements up to +/- 8g on each axis. It supports conversion rates up to 3kHz and consumes only 1μA in sleep mode, or 200μA in active operation. The physical characteristics of the BMA150 make it ideal for a small, low power application. At the same time, its performance exceeeds the requirements specified in Section 3.

The BMA150 also has an onboard analog to digital converter, providing a 10-bit digital output via SPI or I^2C interfaces. The SPI interface can be operated in 3-wire or 4-wire mode. The default operating mode is 4-wire SPI. This mode was also chosen for this project, based on prior experience with 4-wire SPI and its simplicity. The MSP430 has potential for two SPI drivers. One is used for communicating with the CC2500 transceiver, while the other port is ocnfigured as a UART for serial communication. While it is possible to share the SPI hardware between two slaves, the accelerometer SPI interfaced is "bit-banged" via GPIO ports. There were two three motivations for this decision. First, it minimizes potential software interactions with the networking protocol, as described in Section 5.2. Second, a colleague had interfaced the BMA150 in same way and could provide assistance with any issues. Third, the decision simplified trace routing between the microcontroller and the accelerometer because any GPIO pin can function as any of the SPI signals. Each SPI signal from the accelerometer was connected to the microcontroller pin that was spatially closest.

The BMA150 also provides an interrupt signal to notify when a new sample is available or if certain environmental conditions are met. The interrupt signal was connected to an adjacent GPIO pin on the MSP430. Although the current software does not utilize the interrupt, future firmware could save power by sleeping the microcontroller until it is awoken by an external interrupt due to an accelerometer event.

Daughterboard Interface

By separating the power system into a separate daughterboard, the Sensor/RF board requires a hardware interface to the daughterboard. The programming signals will also come from the daughterboard to avoid the need for a separate programming header. Instead, the programming header will be located on the daughterboard in development configurations. Finally, the daughterboard interface has two auxiliary connections connected to the microcontroller. The auxiliary connections can function as either digital I/O, or as an analog input to the ADC on the MSP430. Future daughterboards utilize the auxiliary connections for functionality like analog sensors, input switches, or status outputs. A digital sensor could even be used if it had an interface that needed two or fewer connections.

Pin	Signal	Description
1	RXD0	UART RX
2	VCC	Power supply
3	TEST/SBWTCK	Programmer
4	RST/SBWTDIO	Programmer
5	GND	Common ground
6	TXD0	UART TX
7	ADC_IN0	Aux Analog/GPIO 0
8	ADC_IN1	Aux Analog/GPIO 1

Table 2: Daughterboard Interface Pinout

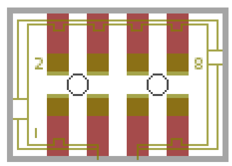

Figure 4: Daughterboard Interface Pinout - Top View

The daughterboard interface is designed so that the daughterboard will sit on top of the Sensor/RF board and connect through Molex 2mm connectors in a 4x2 pin configuration. The male connector is shrouded and mounted on the Sensor/RF board, while the female connector is attached to the bottom of the daughterboard. The interface pintout is shown in Table 2 and Figure 4.

Layout

The Sensor/RF board was laid out on a 1.45" x 2.00" 2-layer PCB. The free license of Eagle only permits 2-layer designs, which are also cheaper to manufacture. However, the design required a ground plane. As a compromise, the bottom signal layer contains a ground polygon that is isolated from other traces on the bottom layer. This solution allows for a easily accessible, low resistance ground connection with a 2-layer PCB. Traces were kept away from the bottom layer near the CC2500 and antenna circuitry to prevent coupling and control impedences for the RF signals.

In general, power supply traces were 16mils except from a decoupling capacitor to an IC. The pad pitch on the IC's was too small to connect a 16mil trace within spacing constraints. These connections were made with 10mil traces, and were always short. All other connections were made using 10mil traces, with the exception of RF traces. Trace widths for these traces were modeled on the EZ430-2500RF design to ensure proper characteristic impedence.

Pin	Signal
1	RXD0
2	VCC
3	TEST/SBWTCK
4	RST/SBWTDIO
5	GND
6	TXD0

Table 3: Programming Header Pinout

4.3 Development Power Daughterboard

Due to the reasons discussed in Sections 4.1 and 6.1, the development version of the power daughter board was designed without power harvesting circuitry. Instead,the daughterboard was designed for convenience in a lab environment and testing functionality of the Sesnor/RF board. One important feature is that the daughterboard supports multiple power sources. On a test fixture, the system needs to be battery powered. To satisfy this need, the daughterboard contains a CR2032 battery holder. The CR2032 is convenient because it has a low profile, operates at 3V, and can still power the system for several hours depending upon duty cycle. When available, the daughterboard can be powered using an external voltage source, or from a TI programmer. The power source is selectable using a jumper.

The development version of the daughterboard also needs to faciliatate programming firmware onto the microcontroller. All signals required for programming are routed to the Sensor/RF board through the interface connector. The daughterboard also contains a 6 pin 0.05” pitch header that mates with the TI MSP ez-430U programming/debugging interface, shown in Table 3. UART signal directions are with respect to the target microcontroller.

Finally, the daughterboard exposes the two auxiliary connections to the microcontroller. ADC_IN0 is connected to the wiper of a 10kΩ trimpot between VCC and GND. The trimpot allows testing of the microcontroller ADC without utilizing any other sensors. The ADC_IN1 connection is exposed on a pin for testing with other sensors or sources.

4.4 Production

Board fabrication was outsourced to Advanced Circuits Corporation (www.4pcb.com). Advanced Circuits provided the best combination of cost, tolerances, and turn time in small runs for this application. Advanced Circuits also provides a Design Rules Check website that will highlight potential problems without formally placing an order. This website was especially useful during the design process.

Due to the number of small components, assembly of the Sensor Board was outsourced to Advanced Assembly, LLC (www.aapcb.com). Advanced Assembly provided the best quote of three assembly companies that were contacted.

5 Software Design

Software design was completed by Joshua Sirkin for an independent Masters of Engineering project in the Department of Mechanical and Aerospace Engineering. The design is relevant to the project as a whole and is summarized here for completeness. Software design was completed on a TI EZ430-2500RF development board. The same board was used as the basis for the Sensor/RF board in attempt for software compatibility.

5.1 Wireless Communication

Wireless communication is accomplished using TI's SimpliciTI™network protocol. The protocol is open source and configured to run out of the box on TI MSP430 microcontrollers in combination with TI transceiver chips. The stack is optimized for low power usage in point to point or star configurations. Despite its robust operation, SimpliciTI has a simple five command API. These characteristics made SimpliciTI™an ideal choice for the wireless communication implementation in this project. Sample code existed for sensor applications that served as a basis for this project.

SimpliciTI™is configured in a hub-spoke topology to allow multiple sensor units to report to one base station. The base station is another TI EZ430-2500RF connected to a desktop computer. The computer receives data from the base station over a USB-to-Serial interface. At this point, the data can be processed in realtime using any desktop application, such as Matlab.

5.2 Accelerometer Interface

As described in Section 4.2, the accelerometers are interfaced using 4-wire SPI. The decision to "bit-bang" the SPI interface was motivated by software design considerations. "Bit-banging" refers to using GPIO pins for SPI communicaition rather than the hardware SPI driver in the microcontroller. This approach brings added complexity by managing the clock and data lines in software instead of simply reading and writing a hardware register. However, this approach can simplify software design when the hardware SPI controller is already being used. In this case, SPI is being used by the SimpliciTI™to control the CC2500 RF transceiver. Although it is possible

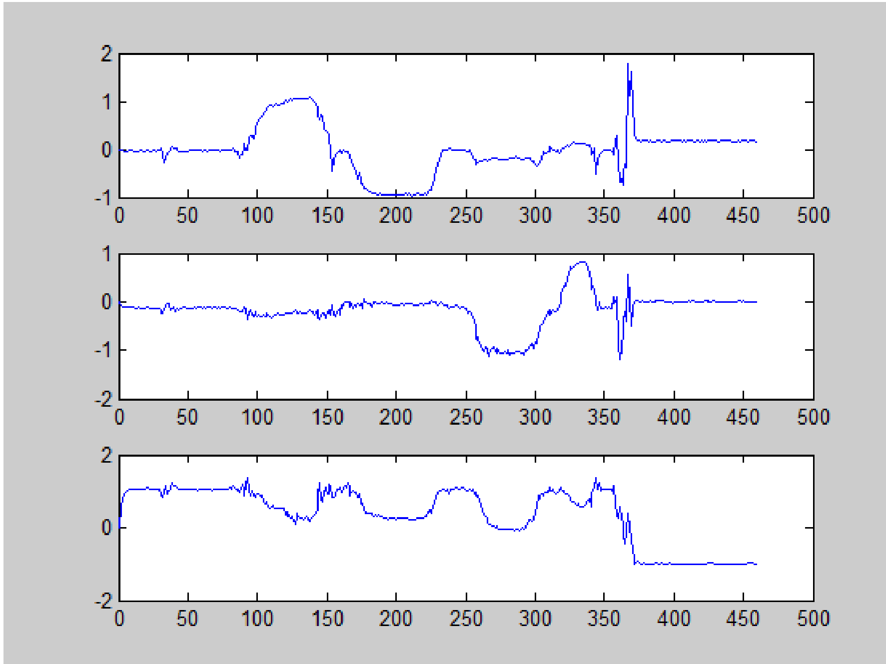

Figure 5: X-Y-Z Accelerometer Data

to share the hardware controller, it could have interfered with the operation of the SimpliciTI™stack. Controlling the accelerometer SPI interface through GPIO pins simplifies interaction with SimpliciTI™.

5.3 Operation

The general operation of the software proceeds as follows:

1. Establish link to base station, repeat if failure
2. Wait for channel to be clear
3. Read new accelerometer data
4. Transmit time-stamped accelerometer data
5. Wait for ACK, resend if no ACK
6. Wait for channel to be clear and repeat

Future software developments will include the ability to configure a slower sampling rate for the accelerometer to allow the end user to control the tradeoff between data resolution and power consumption.

Figure 5 shows a Matlab interface that processes received accelerometer readings and graphs the X, Y, and Z components of the acceleration in real time.

6 Testing and Results

6.1 Power Harvesting

Eric Wolff, with the Laboratory for Intelligent Machine Systems (LIMS) tested the piezoelectric flapper in a wind tunnel. The pizeoelectric actuator was attached to beams of various lengths. In each test, the beam had an airfoil at the end to induce oscillations due to the oncoming airflow. With the wind tunnel operating at 26.7mph, the 9.0cm beam generated the greatest power. The results are summarized in Figure 6.

As seen in the figure, the piezoelectric harvester generated a maximum power of 0.11mW in the test environment. The power budget from Section 3 estimated an average power requirement of 7.3mW. From this data, the piezoelectric harvester does not generate enough power to operate the system. The shortcoming is so large that the piezoelectric harvester does not seem practical even as an auxiliary power source to be used for charging a battery. While piezoelectric harvesting has been used to power devices with transmit powers of up to 20mW, these devices had a duty cycle of less than 0.01%, transmitting once every 17 seconds [2]. Members of the LIMS team continue to explore power harvesting techniques. For example, Matt Bryant [1] independently obtained 2mW of power output from a piezoelectric actuator in a different configuration. Neither case provided sufficient energy to meet the estimated power budget of the sensor system. As a result, the power harvesting aspect of the project was set aside to focus on board design. Hopefully further research and optimization will improve power output from piezoelectric materials and they can be integrated into future work (see Section 7).

6.2 Development Power Daughterboard

The first revision of this board suffered from a glitch in the design software where one net was not connected. Luckily this error was discovered before sending the design files for production and was corrected. The boards were received and assembled by hand. Initial continuity checks to verify all connections indicate that the board is functional. The assembled board is shown in Figure 7.

Design documentation is shown in Appendix B.

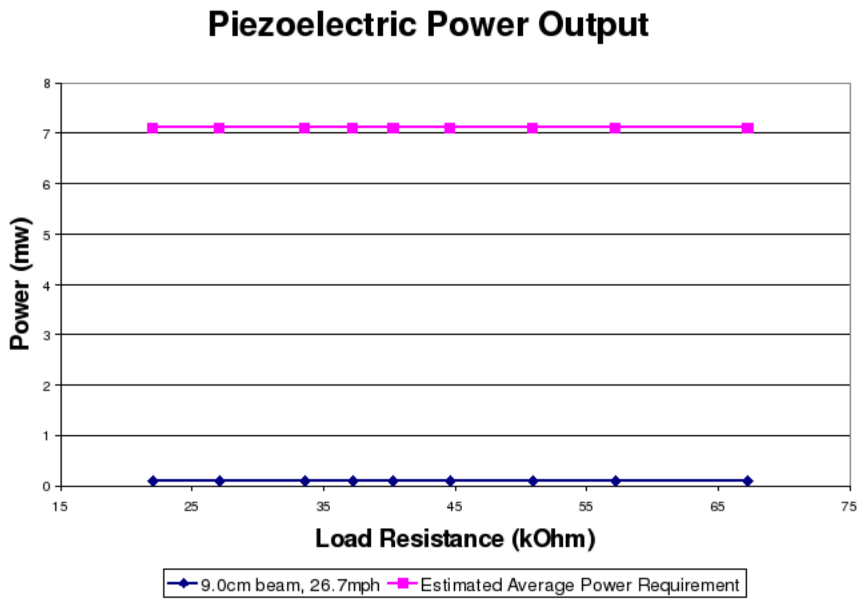

Figure 6: Piezo-electric Power Output

6.3 Sensor/RF Board

Revision 0 of this PCB was produced by Advanced Circuits, shown in Figure 8. During the engineering verifcation process, Advanced Assembly discovered that the Pin 1 designator for the accelerometer was inconsistent with the pinout of the chip. The board design required the creation of a PCB footprint for the accelerometer. During this process, the pinout for the chip was mistaken to be a top view instead of a bottom view. Thus, the footprint and connections on Revision 0 of the PCB were a mirror image of the desired layout.

Fixing the traces on the board by hand would have been difficult. The remaining options were to mount the accelerometer upside down with glue and test leads, or to fix and refabricate the boards. The engineering department at Advanced Assembly was seemed hesitant to mount the chip upside down. Additionally, we determined that the extra cost of fabricating new PCBs was worth the improved quality in the end-product. The problem was quickly fixed and Revision 1 was sent to Advanced Assembly for both fabrication and assembly.

Between the design of Revision 0 and Revision 1, suppliers stopped carrying the BMA150 accelerometer. Luckily, Bosch produces a similar accelerometer, the BMA020. This accelerometer was determined to be both package, pin, and interface compatible with the BMA150. The acceleration ranges are also the same. The only notable difference is that the BMA020 does not have an integrated thermometer. More importantly, Digikey still

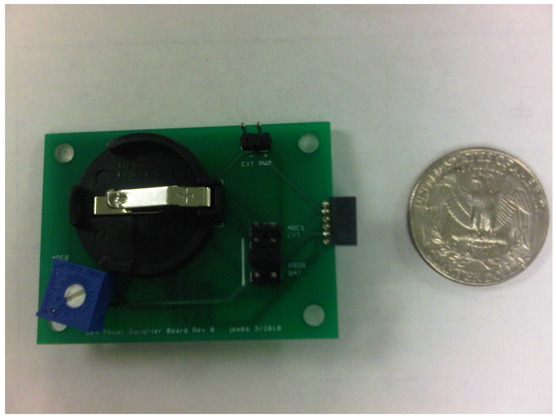

Figure 7: Assembled Power Daughterboard

stocked the BMA020. Thus, Revision 1 of the Sensor/RF Board was actually assembled with BMA020 accelerometers instead of the listed BMA150. Both the hardware and software designs should accept either accelerometer in future spins.

Testing the board involved three main phases. First, basic microcontroller operation such as programming and GPIO interaction was verified. Second, the interface to the accelerometer was tested. The third function tested was the boards ability to connect to an eZ430 board serving as an RF access point.

The first and second testing phases were accomplished simultaneously by using the development accelerometer test code. The code continuously reads accelerometer data and outputs it to the UART, fulfilling phase two of testing. The code was modified to blink LEDs as well in case the UART did not work. The board successfully programmed and began flashing both LEDs. The accelerometer data was accessible by connecting Hyperterminal to the USB-to-Serial converter within the programmer. The test code only accesses one axis of the accelerometer. As expected, the values changed when moving the board with a clear correlation to a single axis of motion.

For the third phase of testing, the board was programmed as a SimpliciTI™end device. This test required another eZ430 configured as an access point for the end device to link to on bootup. The LEDs on the end device blink once per second while attempting to link to the access point. Unfortunately, the Sensor/RF board was not able to link to the access point. Another end device was tested to ensure that the access point was functional. The Sensor/RF board was also programmed as an access point to see if any form of RF communication worked. The other end device was not able to connect to the Sensor/RF mode in this operation. The SPI interface to the CC2500 appeared to be functional, implying a problem in the RF circuitry.

Another strange issue is that the microcontroller did not seem to retain program code after a power loss. The board executed code after programming, but would did not

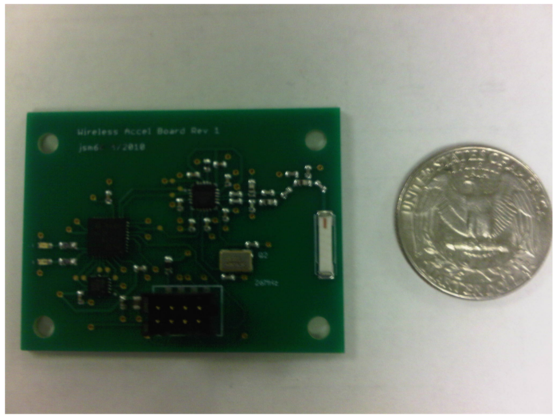

Figure 8: Revision 1 Sensor/RF Board

execute anything after a power cycle until it was reprogrammed.

Both of these issues will be investigated further after the submission of this report.

Design documentation is shown in Appendix A.

7 Future Work

This project has laid the groundwork for future development in wireless sensing for helicopter blades. The project was designed to be adapted to a different power system with minimal additional engineering effort. The daughter board interface contains two extra connections that can be used for digital I/O or analog input. This expandibility will ease the characterization of other power harvesting methods. The interface also allows integration of additional sensors, especially ones with analog outputs.

The characterization and analysis of other power sources and sensors will assist in refining the development versions in this design. Ideally, the entire system will be integrated into a single, smaller circuit board after this phase.

8 Acknowledgements

I would like to thank Professor Bruce Land for his extensive knowledge, advice, and entertainment throughout the past two years. He has been invaluable as both as a professor and as an advisor while encouraging multidisciplinary thinking and practical analysis.

I would also like to acknowledge current and former members of the Laboratory for Intelligent Machine Systems for assistance. Specifically, Eric Wolffe for providing piezoelectric testing data and Rob MacCurdy for assistance with interfacing the accelerometers. Joshua Sirkin also wrote the software that allowed the hardware to come to life.

Finally, this project would not have been possible without Austin Fang and the Sikorsky Airfcraft Corporation who provided the inspiration and resources to make it a reality.

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[5] Texas Instruments. eZ430-RF2500T hardware design files, March 2009.

[6] Texas Instruments. MSP430x22x2, MSP430x22x4 mixed signal microcontroller datasheet, May 2009.

[7] G.K. Ottman, H.F. Hofmann, A.C. Bhatt, and G.A. Lesieutre. Adaptive piezoelectric energy harvesting circuit for wireless remote power supply. *Power Electronics, IEEE Transactions on*, 17(5):669 – 676, sep 2002.

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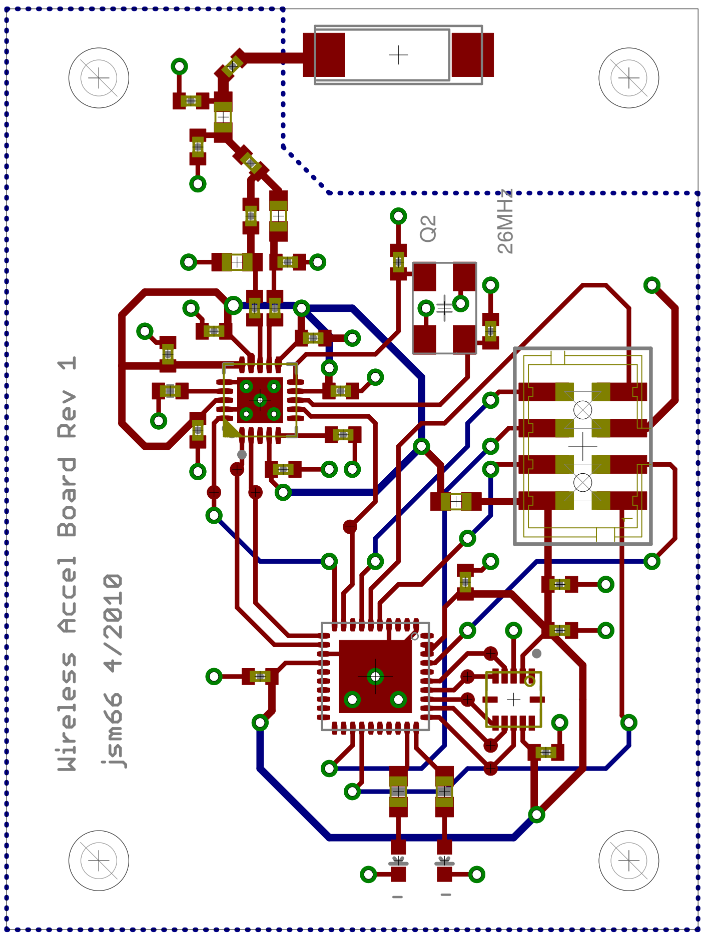
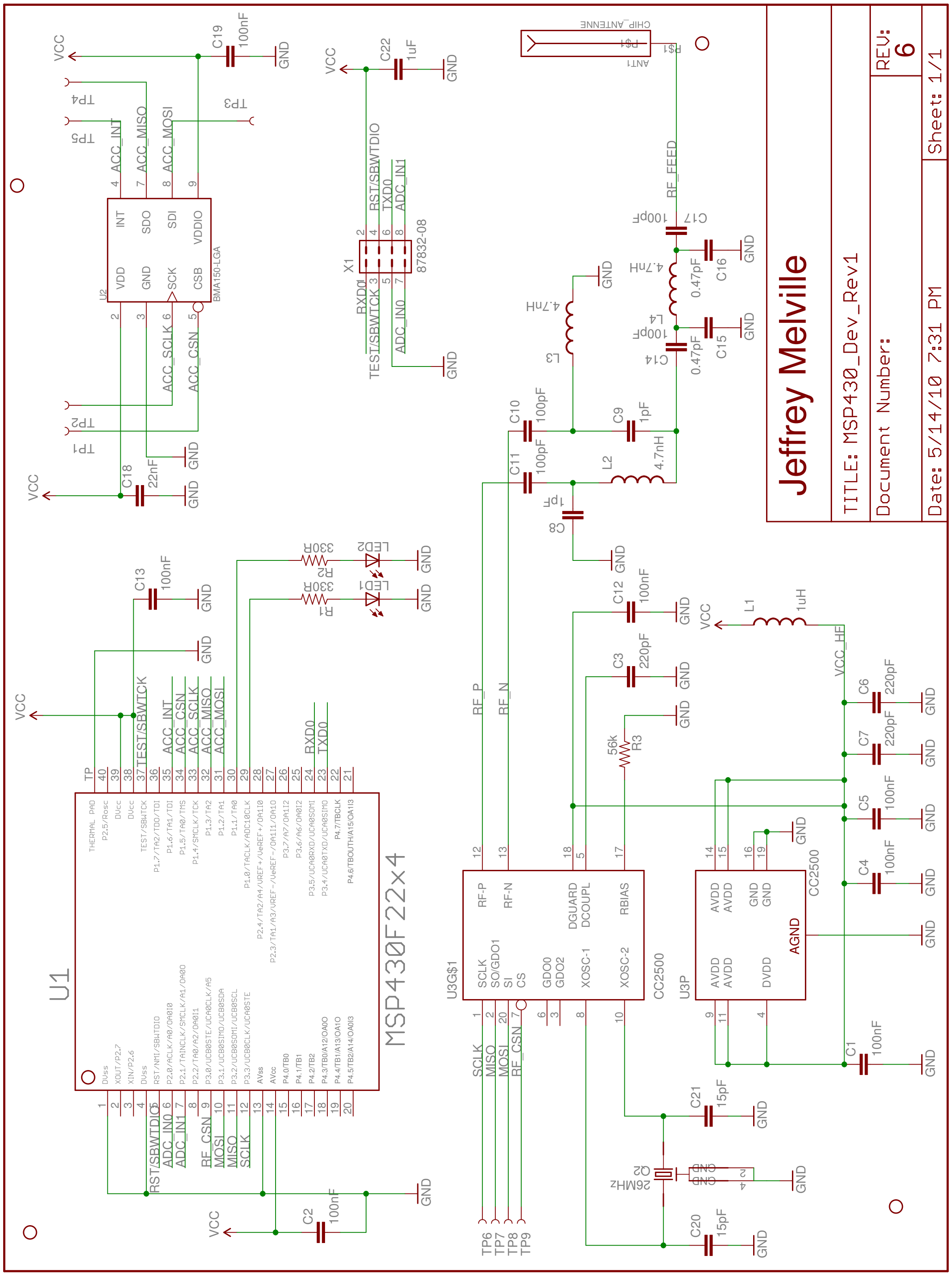
A Sensor Board Design Files

A.1 Layout



A.2 Schematic



A.3 Bill of Materials

Count	Ref_Des	PartNum	Value	Package	Description	Notes
1	ANT1	7488910245	N/A		Wurth SMT Antenna	
7	C1, C2, C4, C5, C12, C13, C19	C0402C104K8RACTU	100nF	402	Cap 100nF 0402-	
3	C3, C6, C7	C0402C221K5RACTU	220pF	402	Cap 220pF 0402-	
2	C8, C9	UVK105CH010BW-F	1pF	402	Cap 1pF 0402-	
4	C10, C11, C14, C17	C0402C101J5GACTU	100pF	402	Cap 100pF 0402-	
2	C15, C16	500R07S0R5AV4T	0.47pF	402	Cap 0.47pF 0402-	Actually 0.5pF
1	C18	C0402C223K4RACTU	22nF	402	Cap 22nF 0402-	
2	C20, C21	500R07S150JV4T	15pF	402	Cap 15pF 0402-	
1	C22	C0805C105K4RACTU	1uF	402	Cap 1uF 0402-	
1	L1	LK16081R0K-T	1uH	603	Inductor 1uH 0603	
3	L2, L3, L4	HK16084N7S-T	4.7nH	603	Inductor 4.7nH 0603	
1	LED1	LTST-C190GKT	None	603	Other LED-0603	Green
1	LED2	LTST-C190CKT	None	603	Other LED-0603	Red
1	Q2	ABM3B-26.000MHZ-10-1-U-T	26MHz	532	26 MHz Oscillator	
2	R1, R2	CRCW0603330RFKEA	330R	603	Res 330R 0603-	
1	R3	CRCW040256K0FKED	56k	402	Res 56k 0402-	
1	U1	MSP430F2274IRHA	None	RHA40	IC F22X4---RHA40 RHA40	
1	U2	BMA020	N/A	LGA12	Bosch Accelerometer	
1	U3	CC2500RTKR	N/A	QFN50	CC2500 RF Transceiver	
1	X1	87832-0820	N/A		Molex 8-pin connector	

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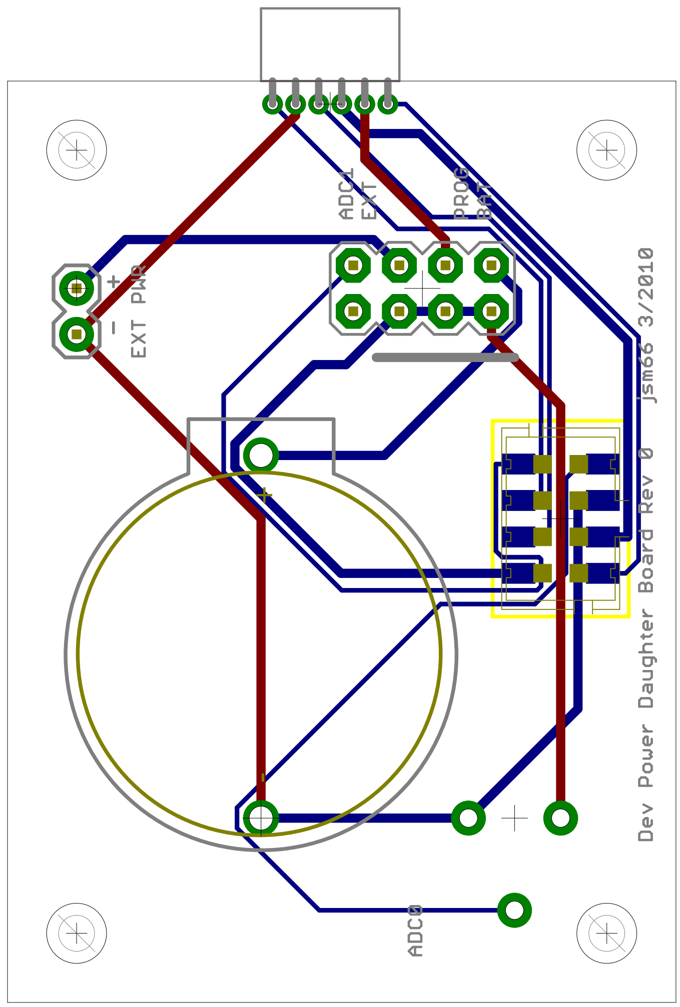
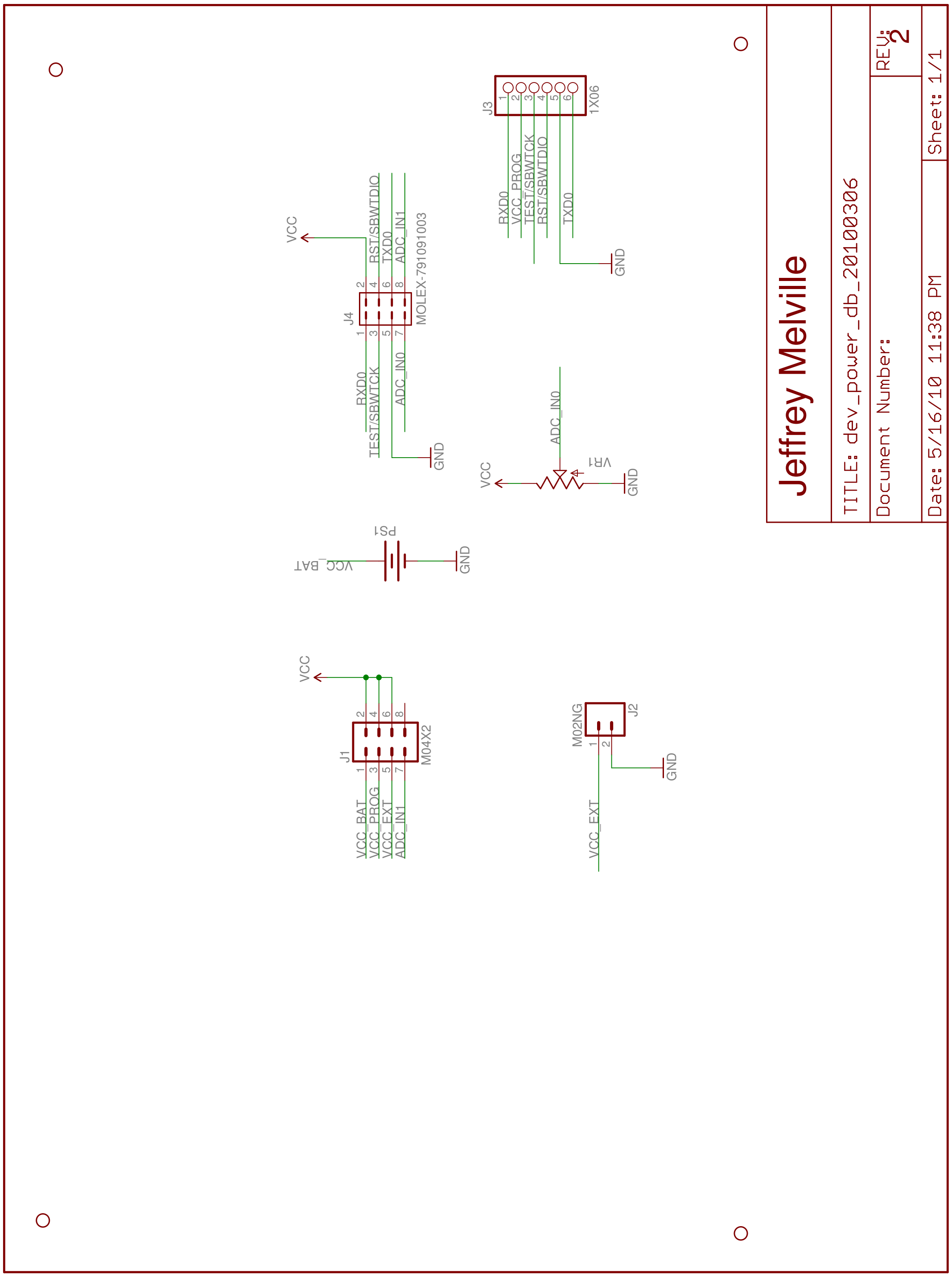
B Development Power Daughterboard

B.1 Layout



B.2 Schematic



B.3 Bill of Materials

Count	Ref_Des	PartNum	Value	Package	Description	Notes
1	J1	M04X2	N/A		Jack M04X2 2X4	
1	J2	M02NG	N/A		Jack M02NG 1X02	
1	J3	LPPB061NGCN-RC	N/A		Mill Max 0.050" 50pin Socket (Sullins)	
1	J4	791091003	N/A		Jack MOLEX-791091003 CON-2X04	
1	PS1	BH32T-C	N/A		20mm coin cell holder	
1	VR1	3386F-1-103LF	10k		Bourns 3386 10k Trimpot	Orig 3386P

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